Microlenses immersed in nematic liquid crystal with electrically controllable focal length

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A microlens immersed in a nematic liquid crystal cell has been constructed with a variable focal length which can be controlled by applying an analogue voltage to the nematic liquid crystal. The focal length is -910 ± 30 μ m with no electric field applied and with an applied field the focal length can be varied from 380 ± 50 to 560 ± 20 μ m although at present the lens performance is limited by aberrations.

Introduction

A variation of the overall focal length of an optical system is required if the object being imaged is not in a fixed position. Commonly, this variation would be provided by a mechanically driven shift of the separation between a combination of lenses. The technology of liquid crystals with their electrically controllable birefringence may provide an alternative which can be varied quickly and simply and yet still uses available and established manufacturing processes. The glass of a normal macro lens has been replaced with liquid crystal [1] but as typical macro lenses are very thick by the standards liquid crystal cells, very long times are needed for the liquid crystal to achieve a stable equilibrium state.

To avoid these problems a diffractive structure can be used thereby only requiring cell thicknesses compatible with liquid crystal properties, e.g. a Fresnel lens (patterned electrodes)[2] or liquid crystal over a surface relief hologram[3]. However, such structures have only one focal length (in the case of the lens) for any wavelength or one diffraction efficient output (generated image) and are, therefore, simply switchable. Obviously, the electrode can be pixellated but the minimum achievable pixel size limits the possible focal lengths[4]. One of the most promising variable focal length lenses to date is the liquid crystal microlens[5]. A cell is constructed using electrodes patterned with holes on both substrates (mutually aligned) and then the fringing fields between the electrodes cause the liquid crystal molecules to orientate themselves into what is, optically, a lensing structure. However, the approximation to an ideal lens optical phase profile (i.e. small aberrations) is true only for a limited voltage range.

Such lenses have applications as optical fibre switches and light scattering displays. Incoherent correlators, for commercial applications, require long focal length microlenses. Poon et al constructed a cell of photoresist microlenses immersed in index

matching fluid to reduce the optical power of the lenses[6]. If, instead of index matching fluid, nematic liquid crystal is used as the matching fluid then the possibility arises of variable focal power. Nematic liquid crystal has the property that when a voltage is applied effective liquid crystal refractive index changes for one polarisation. In this paper we describe photoresist microlenses immersed in liquid crystal (as microlenses they are small enough, 50 - 200 μ m diameter, to avoid the problems of cell thickness) so that the power of the microlens can be modulated by the electrically controlled birefringence.

Lens fabrication and characterisation

The microlenses were formed on top of planar electrodes as this was convenient and gives a uniform electric field. The arrays of microlenses were created with the standard techniques [7] by spinning a 20 μ m layer of photoresist (AZ4620A, Hoechst) onto the unusual substrate of Indium Tin Oxide (ITO) coated glass, which gives a transparent electrode. The thickness of photoresist gave 50 and 100 μ m diameter lenses where the curvature, c, was a good approximation to spherical[7], verified with Talystep profiler. A liquid crystal cell was constructed using a second ITO coated glass substrate. Both substrates were coated with Polyvinylalcohol (PVA) and then were rubbed to produce alignment in the liquid crystal. The rubbing directions were arranged to be anti-parallel and the two slides separated with 27 μ m thick Mylar spacers -see fig 1. The cell was clamped together and was filled by capillary action with a nematic liquid crystal with positive dielectric anisotropy (E7, Merck), i.e. the liquid crystal molecules orientate parallel to an applied electric field. Finally, the cell was glued together with UV curable glue.

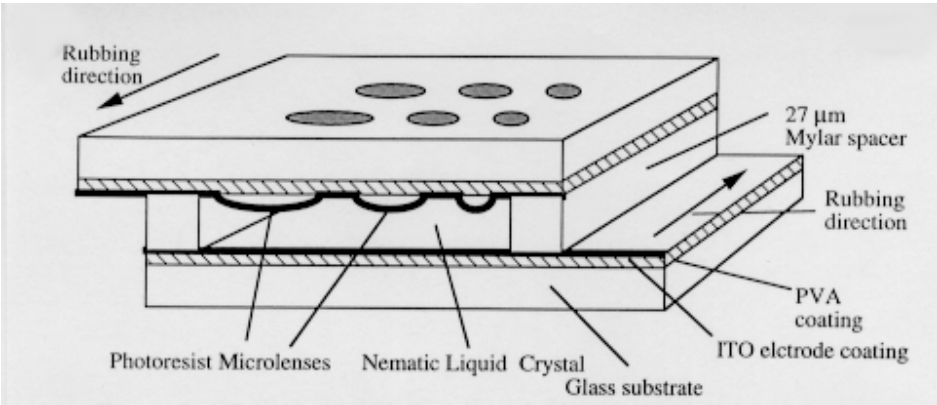

Figure 1: Microlenses immersed in nematic liquid crystal inside cell

The uniaxial birefringent liquid crystal material has an extraordinary refractive index, $n_{\text{liquid crystal}}$, between 1.74 and the ordinary refractive index of 1.52. The liquid crystal can be reorientated by an electric field so that the extraordinary refractive index is modulated between the two values (for light polarised parallel to the alignment direction of the liquid crystal). The photoresist refractive index, $n_{\text{photoresist}}$, is 1.64[6] so that the cell should be able to be a positive or negative lens of focal length, f, or just act as piece of glass when the focus changes from negative to positive. The focal length, f, is given by

$$f = [\ (n_{\text{liquid crystal}} - n_{\text{photoresist}})c\ ]^{-1} \quad (1)$$

A Mach-Zehnder interferometer was built (shown in fig.2) in order to test the quality of the lenses. Polarised light (in the same direction as the rubbing direction) was used incident perpendicular to the cell. Initially, only the test arm of the interferometer was used to make measurements of the focal lengths of the microlenses. The image of the microlens edge was found, then the focal spot was located and the difference of the objective micrometer positions is the measured focal length. Since light was scattered or depolarised by the cell, a polariser (orientated parallel to the laser polarisation and rubbing direction) was placed after the microscope objective when finding the focal spot as the lens has different focal lengths in the two polarisations.

Reinstating the reference arm, interferograms were taken to measure the quality of the lenses. The microlens was placed at the usual working distance of the microscope objective, i.e. at its designed conjugate, to ensure the minimum aberration of the interferometer. A long working distance objective (4mm) was used since the focus of the lens was inside the cell's glass substrate. The substrate with the microlenses was placed nearest the objective to minimise aberrations (fig. 2). The CCD camera (via imaging optics) was positioned to image the back image plane of the objective. The resultant curvature of the wavefronts in the test arm was matched in the reference arm by placing a lens in the position which gave straight fringes across the lens image. The interferogram was recorded by a frame grabber/video printer from the CCD camera which was imaging the microlens aperture. These interferogram pictures were digitised as fringes using a graphics tablet connected to a PC running a fringe analysis program (Moeller Wedel "Informatic-F").

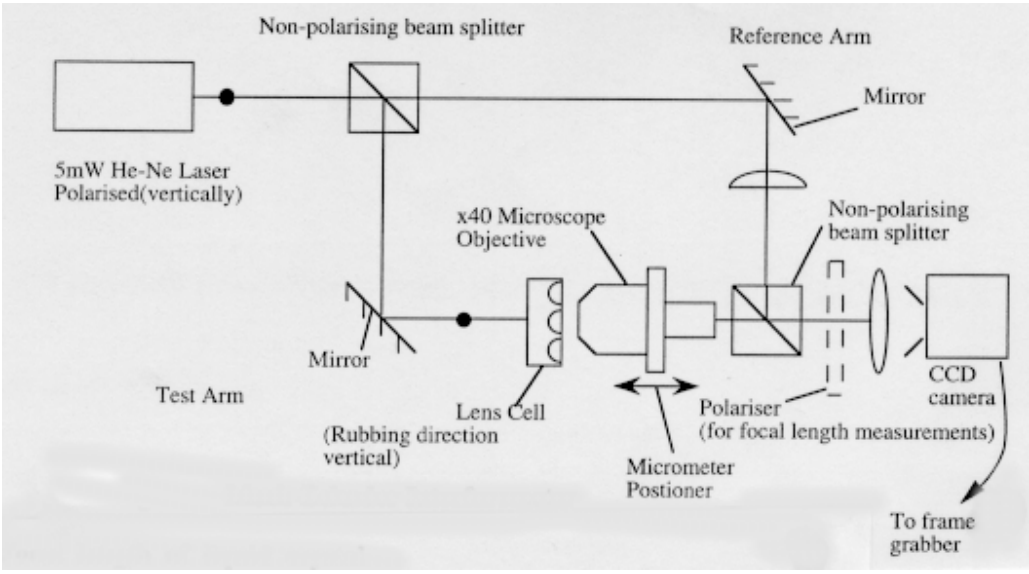

Figure 2: Mach-Zehnder Interferometer

Results: Focal length and lens aberrations upon switching

The focal length measurements for the lens, as shown in fig. 3, were measured in two ways; directly, as described above and from the fringe analysis, as explained below. Clearly, the lenses are not behaving in accordance with the simple model of equation (1) although there is a variation of focal length and the expected discontinuity going from negative to positive focal length. The focal length measurements for the region where the liquid crystal was switching rapidly were not practical as the focal spot was too ill defined at low voltage. The fringe analysis program fits a best focus phase (and aberrations) to the fringes, however, since the reference beam is not a plane wave, the focus it calculates is the extra focus relative to the reference. To obtain the focal lengths from the fringe analysis, as plotted in fig. 3, the difference in focus was recorded (without moving the reference beam) from the best focus fits at each voltage relative to the fit of best focus at the highest voltage (11.63V). Then the results were deduced by adding that difference to the focal length measured directly at the highest voltage.

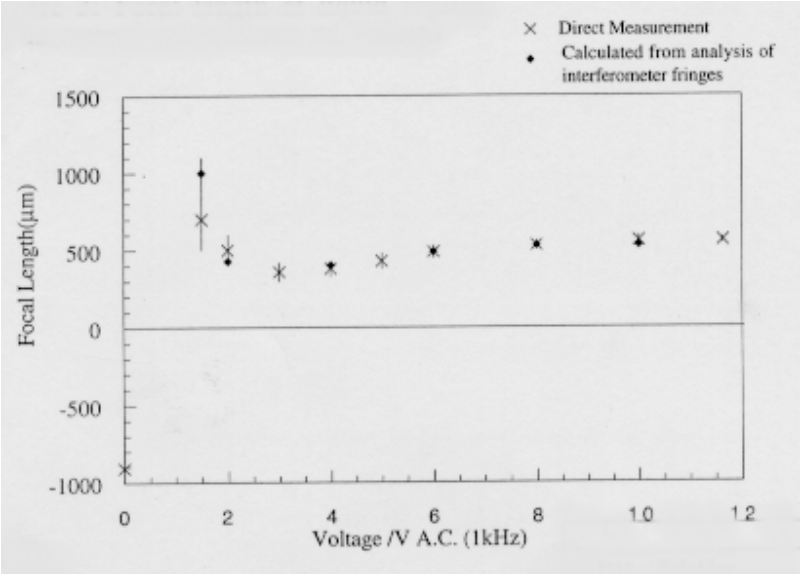

Figure 3: Focal length of liquid crystal immersed microlenses vs. voltage

For a more complete analysis of the cell behaviour, the aberration results obtained from the fringe analysis should be considered (see fig.4). The diagram shown is a map of the phase of the light exiting the aperture of the microlens but with the focus term removed (by the computer), i.e. a lens which focused perfectly would give a flat phase map. The common features of the phase maps at different voltages are a dip in the middle and a fall off at the bottom edge. Both aberrations become smaller as the voltage is increased.

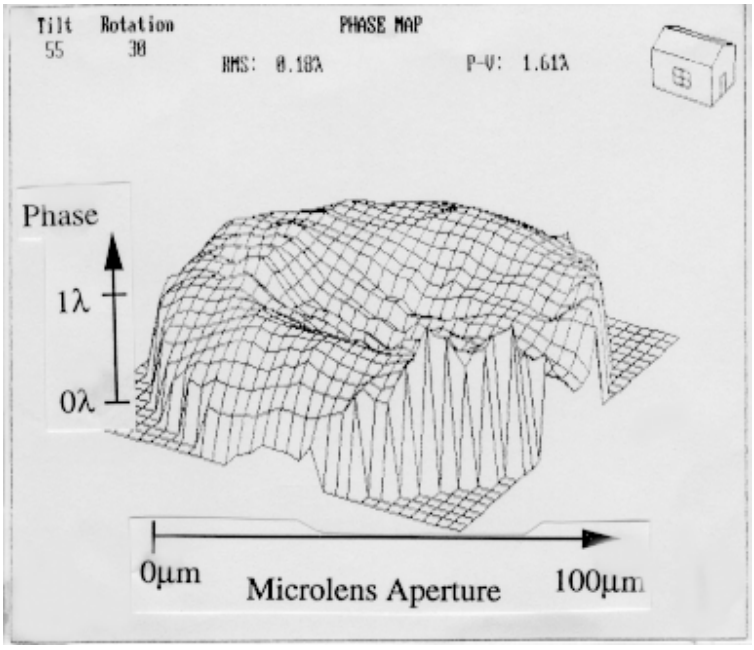

Figure 4: A map of phase exiting the microlens (at 6V) but with the best fit focus removed

To understand these features, the assumptions of the simple model should be considered. The central dip may be due to extra focusing. The simple model of the lens cell treats the liquid crystal cell as homogeneous in the plane of the cell, i.e. it ignores the distortion of the cell walls by the microlens. The cell thickness and parallelism vary due to the microlens which affects the liquid crystal structure. The cell is thinner at the centre of the lens so the resistance to deformation by the electric field is greater and the liquid crystal will be less tilted, therefore, the refractive index is higher at the centre than at the edge and a dip in the phase map is seen.

The fall off is perhaps due to the non-parallelism of the cell walls affecting the liquid crystal orientation. The liquid crystal switching works best when the substrate induces a pre-tilt in the crystal when no field is applied, otherwise it can switch either way in an electric field (no preferred orientation) and regions of opposing tilts can form. A small pretilt ($\approx 1°$) occurs using PVA but obviously on one side of the lens this is cancelled out by the profile of the lens ($\approx 40°$ relative to substrate at edge). This causes a disclination when the liquid crystal cell is turned on which dies away due to torsional forces in 10 to 60 seconds. However, in the region of opposing pretilt the liquid crystal must turn through a larger angle which results in a larger average index (averaging along a line perpendicular to the cell). The rise in the focal length above 2V is probably due to a shift in the best focus as the aberrations which cause a shorter focal length die away.

Conclusion

A microlens with variable optical power has been built and the focal length has been modulated from -910 ± 30 μ m, with no voltage applied, to between 380 ± 50 and 560 ± 20 μ m above the liquid crystal threshold voltage. At present the lens is limited by uneven switching of the liquid crystal due probably to the non-planar cell walls which cause the liquid crystal to have an inhomogeneous effective refractive index. Aberrations have been correlated with the uneven regions in the structure of the liquid crystal.

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